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for

RESEARCH AND DEVELOPMENT OF CRYOGENIC PROPELLANT

FEED SYSTEMS FOR ELECTROTHERMAL ENGINES

Prepared for

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RESEARCH AND DEVELOPMENT OF CRYOGENIC PROPELLANT

FEED SYSTEMS FOR ELECTROTHERMAL ENGINES

Statement of Work

At the start of the current report period the project group was organized, the work schedule was prepared, and the areas of required additional information were defined. The bibliography prepared under the preceding phase of the work had been brought up to date.

Description of Work

A meeting was held at Cleveland, Ohio, with Mr. H. R. Hunczak, Technical Monitor for NASA, on March 29, 1962. Some of the details of the mission and the vehicle were specified at that time, although a complete mission profile has not yet been defined.

The vehicle will be boosted into a 260 nautical mile Earth orbit. Approximately three hours will then be allowed before ignition of the electrothermal engines, in order that tracking stations can determine the orbit. Several cycles of 45 minutes on and 45 minutes off may then be required to obtain a circular orbit. The engines will then propel the craft to a 24-hour circular Earth orbit (about 22,000 nautical miles). For the hydrogen propellant a rate of 2.76×10^{-4} lb/sec will be required for 120 days with 150 days total stay time. Further details will be obtained from the CONFIDENTIAL Avco report on the 24-hour communications satellite, which has been requested.

The storage tank outer diameter is limited to 10 feet. Heat leakage to the insulated tank will originate at the vehicle skin and at the electrothermal engine. Information on skin temperatures and maximum acceleration of the vehicle will be supplied by NASA at a later date. A period of two hours was tentatively specified for ground time between propellant fill and lift-off.

The engine will operate at 1 to 2 atmospheres pressure. The engine manufacturer will supply a critical flow orifice at the engine intake. The propellant supply pressure must be a minimum of 2 atmospheres multiplied by the critical pressure ratio for sonic flow through the orifice. No temperature limit was specified, although an upper limit may later be set.

Operating conditions for the ammonia propellant systems will be specified at a later date.

based on the operating conditions specified above, calculations of the hydrogen storage tank dimensions and insulation requirements were made. Preliminary sizing of the extraction and flow control system was made. During the month of April an evaluation will be made of alternate methods of pressure control. Studies will be made of the flow control system and the structural design of the storage tank.

Sketches and Drawings

A preliminary sketch of the storage tank, showing the approximate size and shape, is attached. No other sketches or drawings were made during this report period.

Calculations

The following calculations were made during this report period and are attached hereto:

- (1) Thermodynamics of self-expulsion from storage.
- (2) Calculation of storage tank size.
- (3) Calculation of insulation thickness.

Man-Hours Expended

A total of 250 man-hours were expended during the report period. The cumulative total expenditure to date is 330 man-hours, or 10.5 percent of the budgeted 3132 man-hours.

Contract Funds

An estimated \$3,880 has been charged to the contract to date. This sum represents 10.5 percent of the allotted funds.

Other Information

The following information is to be supplied by NASA. It should be made available at an early date if the project is to proceed on schedule.

- a. Skin temperature-time relationship for vehicle.
- b. Maximum acceleration of vehicle.
- c. Specifications for ammonia system.

APPENDIX

In Attachment I it is shown that to obtain constant pressure and constant flow conditions, heat must be supplied to the tank at a constant rate which depends on the thermodynamic properties of the fluid. An equation for predicting this rate is given. Also given are equations for calculating the tank volume and initial propellant mass necessary to provide a given mass of usable propellant at constant pressure.

Figure 1 gives the rate of heat addition necessary; Figures 2 and 3 give the mass of p-hydrogen and the tank volume necessary for operation at various pressures, allowing no initial ullage. These figures are plotted in terms of generalized parameters.

In Figure 4 is plotted the length of a cylindrical tank, 9 feet in diameter, with hemispherical caps, that will store 2910 pounds of usable p-hydrogen to be delivered at a steady rate of 2.76×10^{-4} lb/sec for 122 days (allowing 2 days for maneuvering, etc.)

The data used in the calculations were taken from N.B.S. TN 130, "Provisional Thermodynamic Functions for Para-Hydrogen" by H. M. Roder and R. D. Goodwin.

From the figures it can be seen that the pressure should be chosen as low as possible commensurate with the delivery pressure requirements. This will probably result in a storage pressure in the neighborhood of 60 psia.

This concept will result in a relatively compact and light storage tank because of the high initial density and the low storage pressure.

The heat input to flow ratio will be about 180-200 Btu/lb, which corresponds to about 180-200 Btu/hr at 2.76×10^{-4} lb/sec (0.994 lb/hr). Assuming an outer skin temperature of 500°R, the heat leak would balance this requirement with an insulation thickness of about 1/4" of Linde SI-44. Instead of relying on such a balance, it would be better to use rather more insulation and install a pressure-controlled electric heater. If the insulation thickness were, say, 1/2", the heater duty would be 100 Btu/hr or about 30 W.

ATTACHMENT I.

THERMODYNAMICS

The rate of change of the internal energy of the stored fluid is

$$d(MU_1)/dt$$

The flow rate from the storage vessel is $-dM/dt$ therefore the energy removed from the vessel by flow is

$$-U_2 dM/dt$$

The rate at which this stream does work is

$$-p_2 \bar{V}_2 dM/dt$$

In addition, energy is added to the tank by some independent means at a rate

$$Q$$

By energy balance

$$\begin{aligned} \frac{d(MU_1)}{dt} &= Q + (U_2 + \bar{V}_2 p_2) \frac{dM}{dt} \\ &= Q + H_2 \frac{dM}{dt} \end{aligned} \quad (1)$$

If the temperature in the tank is constant, the pressure will also be constant, as will be the specific internal energies of the phases.

Since material, energy, and volume are conserved

$$m' + m'' = M \quad (2)$$

$$u'm' + u''m'' = MU_1 \quad (3)$$

and

$$\frac{m'}{\rho'} + \frac{m''}{\rho''} = V \quad (4)$$

Combining Equations 1, 2, and 3

$$(u' - u'') \frac{dm'}{dt} + u'' \frac{dM}{dt} = Q + H_2 \frac{dM}{dt} \quad (5)$$

and by combining Equations 2 and 4 and differentiating

$$\frac{dm'}{dt} = \frac{1}{1 - \frac{\rho''}{\rho'}} \cdot \frac{dM}{dt} \quad (6)$$

Substituting Equation 6 in Equation 5

$$\left\{ \frac{u' - u''}{1 - \frac{\rho''}{\rho'}} + u'' - H_2 \right\} \frac{dM}{dt} = Q$$

And since $F = -dM/dt$

$$\frac{Q}{F} = \frac{u'' - u'}{1 - \frac{\rho''}{\rho'}} + (H_2 - u'') \quad (7)$$

It follows from Equation 7 that if F is constant Q is constant.

MATERIAL BALANCE

Since there is a minimum pressure of propellant required for engine operation, the tank must be charged with more propellant than will be used in the mission. For calculation purposes, it will be considered that no more propellant will be available when the liquid phase disappears at the control conditions.

Then

$$F t_M = M_0 - \rho' V \quad (8)$$

Also

$$M_0 = [(1 - \theta)\rho' + \theta\rho''] V \quad (9)$$

Eliminating M_0 between Equations 8 and 9 and rearranging to give an expression explicit in V

$$V = Ft_M / (1 - \theta) (\rho' - \rho'') \quad (10)$$

And eliminating V to give an expression for M_0

$$M_0 = \left\{ \frac{\rho'}{\rho' - \rho''} + \frac{\theta}{1 - \theta} \cdot \frac{\rho''}{\rho' - \rho''} \right\} Ft_M \quad (11)$$

NOMENCLATURE

F : flow rate from tank
H : average specific enthalpy
m : mass of phase in tank
M : mass of fluid in tank
p : pressure
Q : heat leak rate
t : time
u : specific internal energy of one phase
U : specific internal energy of fluid (average)
 \bar{V} : specific volume
V : tank volume
 ϕ : initial ullage (volume fraction)
 ρ : density

Subscripts

0 : beginning of fluid flow
1 : inside tank
2 : discharge line
M : end of mission (or propellant use)

Superscript

primes and double primes indicate liquid and vapor phases respectively.

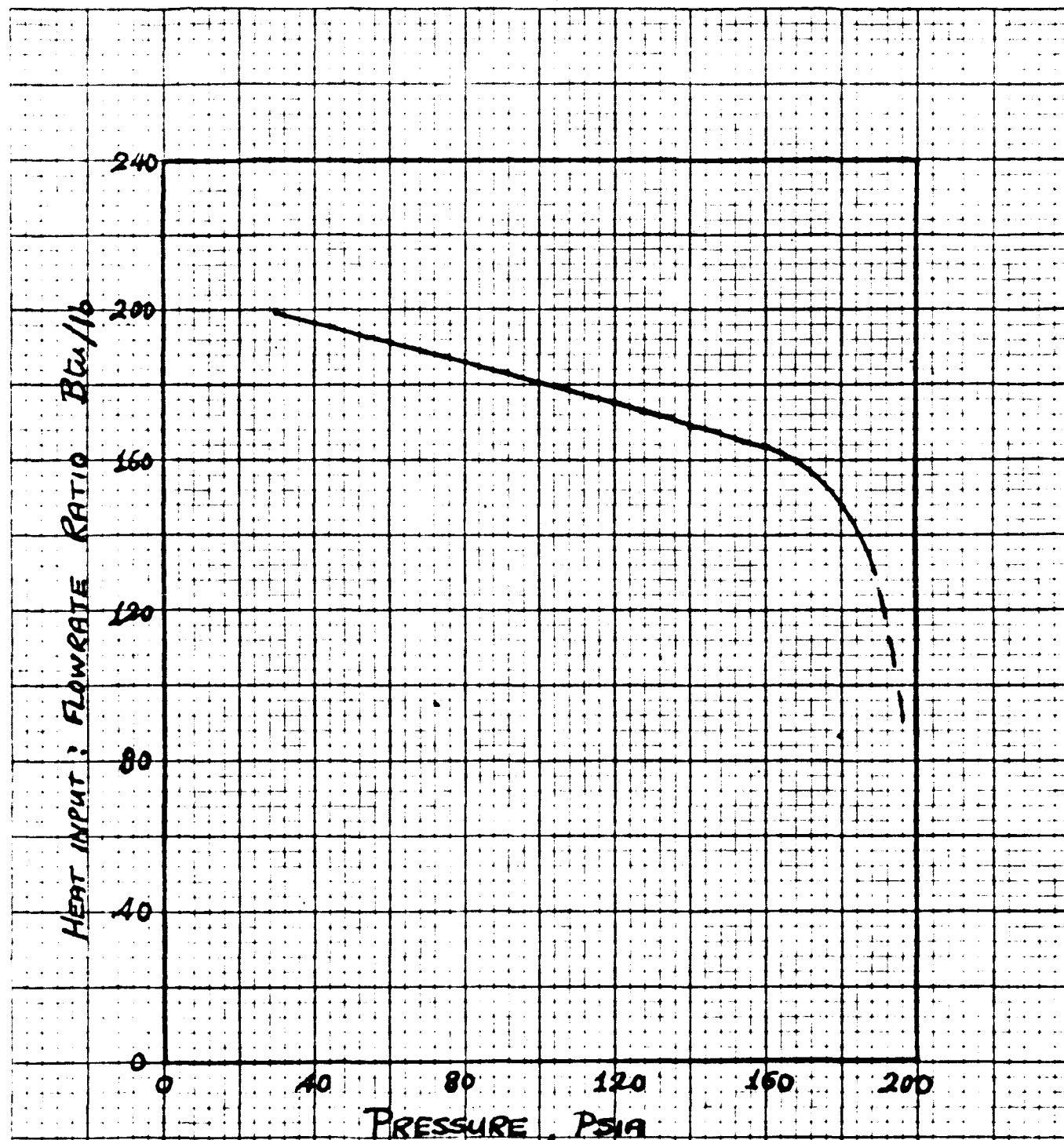


FIG 1 HEAT INPUT : FLOWRATE RATIO FOR
EXPULSION OF GAS FROM A TANK
CONTAINING STORED LIQUID HYDROGEN
BY THROTTLING AND HEAT EXCHANGE
WITH TANK CONTENTS (10 PSI ΔP
ALLOWED)

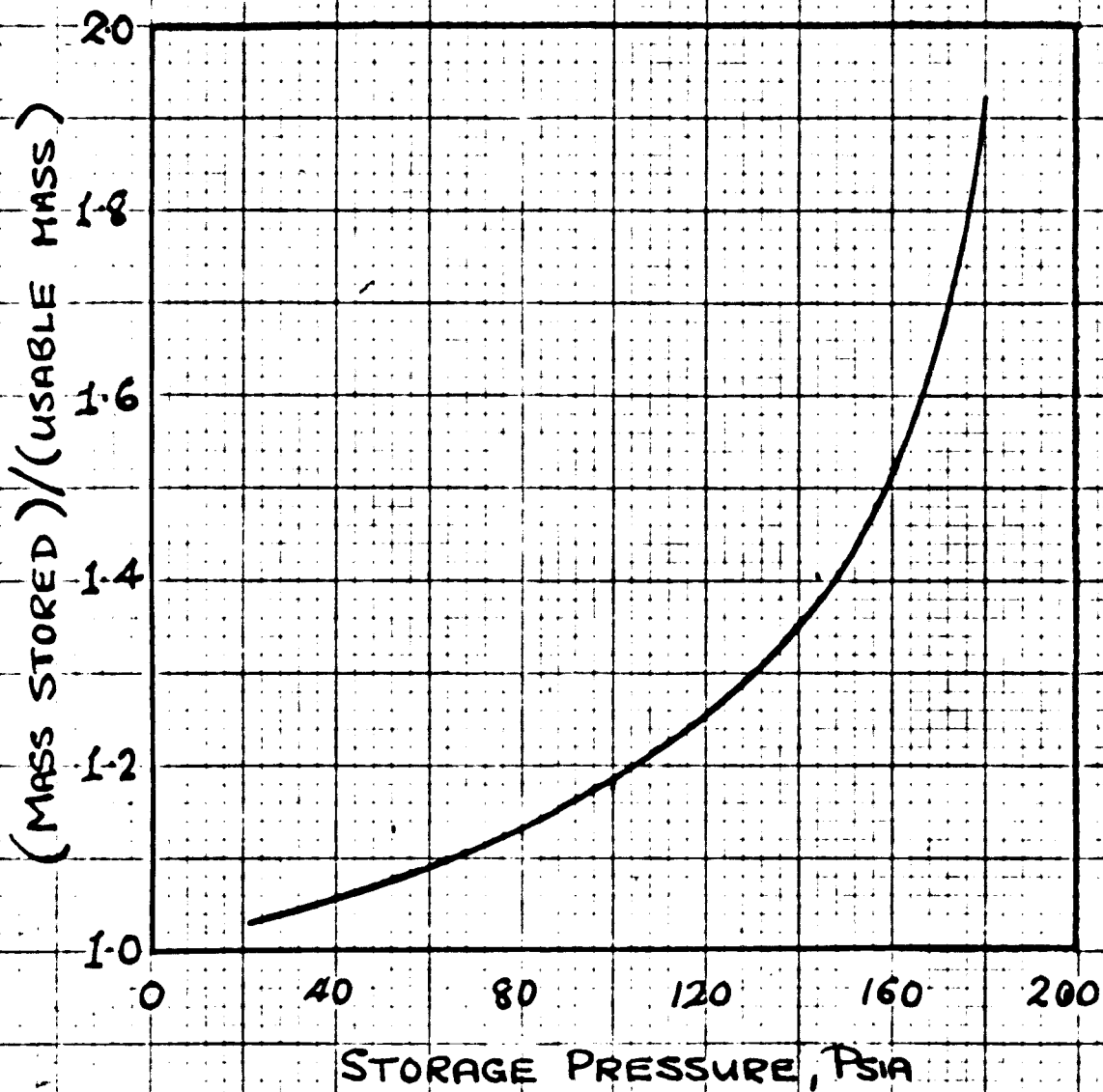


FIG 2 RATIO OF MASS STORED INITIALLY
TO USABLE MASS FOR CONSTANT
PRESSURE STORAGE OF LIQUID
PARA-HYDROGEN. (NO ULLAGE).

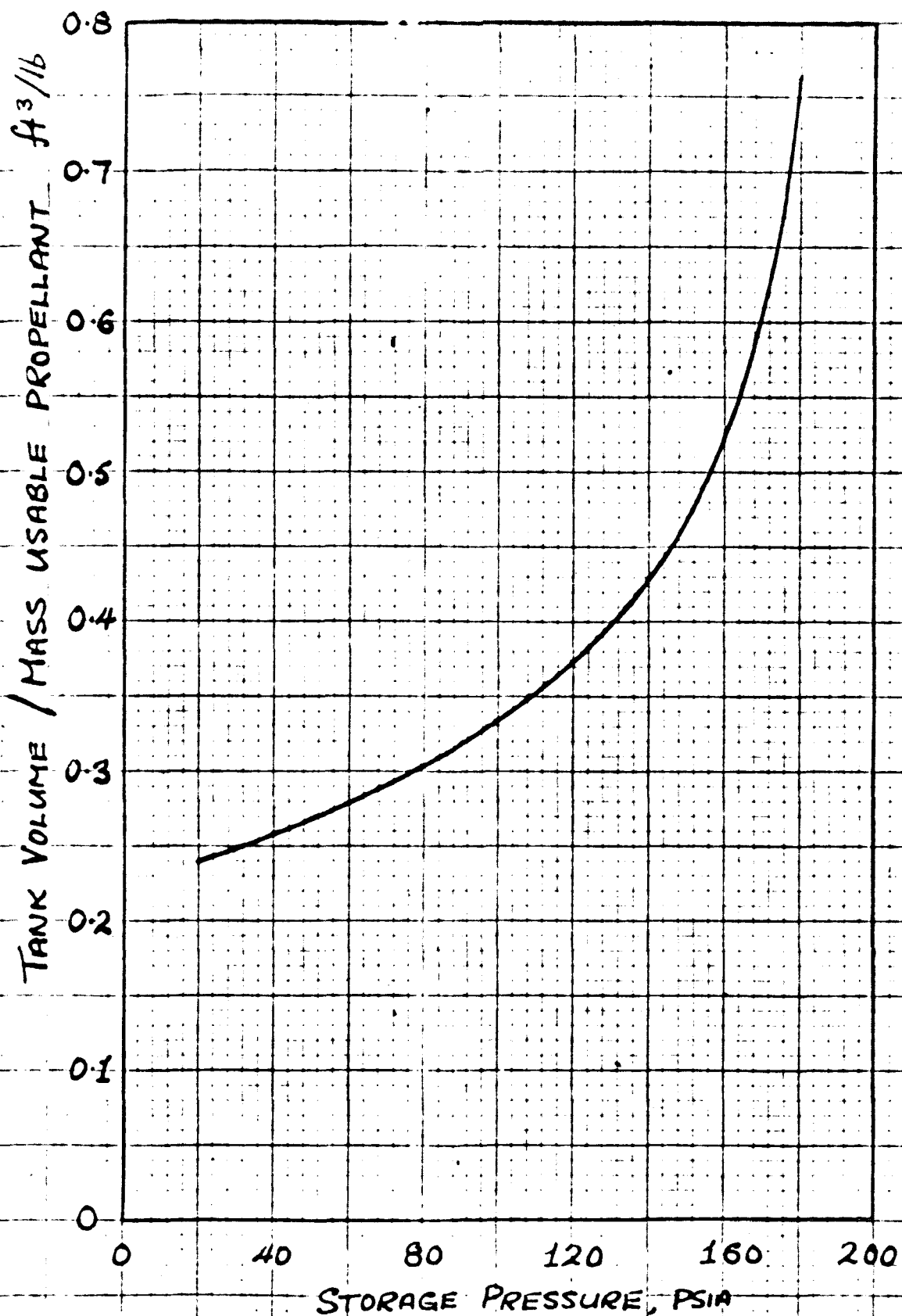


FIG 3 RATIO OF TANK VOLUME TO MASS
OF USABLE PROPELLANT FOR
CONSTANT PRESSURE, NO INITIAL
ULLAGE, STORAGE OF p-HYDROGEN

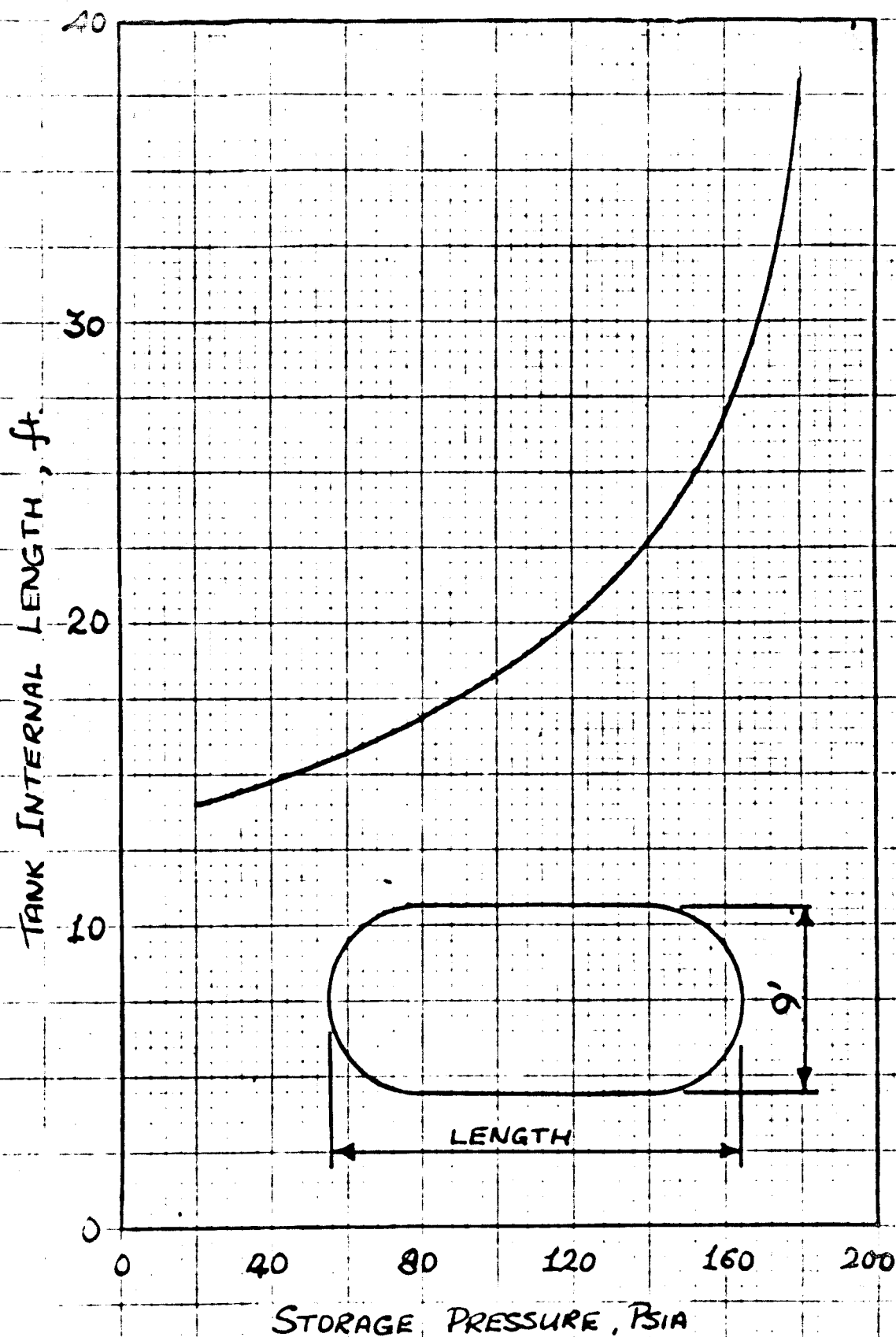


FIG. 4 LENGTH OF CYLINDRICAL TANK (9' ϕ)
WITH HEMISPHERICAL CAPS TO STORE
2910 LB OF P-HYDROGEN AT CONSTANT
PRESSURE